

An Update on the Performance of Li-Ion Rechargeable Batteries on Mars Rovers

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ABSTRACT

NASA's Mars Rovers, Spirit and Opportunity have been exploring the surface of Mars for the last eighteen months, performing astounding geological studies to answer the ever-puzzling questions of life beyond Earth and the origin of our planets. These rovers are powered by triple-junction solar cells during the Martian day. Additionally they have rechargeable lithium-ion batteries, for the first time on a space mission of this scale, for keeping the rover electronics warm, and supporting nighttime experimentation and communications. The use of Li-ion batteries has resulted in significant benefits in several categories, such as mass, volume, energy efficiency, self discharge, and above all low temperature performance. Though designed initially for the primary mission needs of 300 cycles over 90 days of surface operation, both the rovers have far exceeded these expectations, mainly due to the impressive performances from the lithium-ion batteries. After about 500 days of exploration, there is little change in the end-of discharge (EOD) voltages or capacities of these batteries, as estimated from the in-flight data and corroborated by ground testing. Aided by such impressive durability from the Li-ion batteries, both from cycling and calendar life stand point, these rovers are poised to extend their exploration well beyond two years. In this paper, we will describe the performance characteristics of these batteries during launch, cruise phase and on the surface of Mars thus far.

INTRODUCTION

NASA's Mars Rovers, Spirit and Opportunity constitute two of the most successful space exploration missions in the recent past. These two 'robotic geologists' were aimed at examining the surface of Mars and analyzing the core of its rocks to detect the presence of water and, thus, any evidence of life. In addition, they were aimed at providing invaluable information on the geological conditions prevailing on Mars, which will have a bearing on our understanding of its (Mars's) origin.¹ Since their exciting landing on Mars in beginning of last year, these rovers have successfully completed the primary phase of the missions, which includes about 300 cycles over 90 days of operation, and are well into their extended phases, with about 550 Martian sols completed thus far. Several astounding scientific contributions have already been made by both these rovers, including detection of past water at the both the landing sites, located at two ends of the planet, Mars.

The energy conversion system on the rovers is comprised of deployable solar arrays with triple-junction GaInP/GaAs/Ge cells. The BOL (beginning of life) power of these arrays are about 1000W. Over the course of 500 cycles and eighteen months of operation there have been decreases in their power levels, partly due to Martian dust accumulation on the array. However, during a 'friendly storm', these arrays were cleaned to some extent, thus restoring their power level. The energy storage system on these rovers is comprised of lithium-ion rechargeable batteries, used for the first time in such planetary exploration missions of NASA.²⁻⁴ The use of Li-ion batteries, in place of conventional aqueous or alkaline systems, was primarily governed by the power and energy needs for the missions, within the constraints of mass and volume. Alkaline systems would have provided either 25-20 % of the desired energies (e.g., Ni-Cd or Ni-H₂) in the available mass and volume, or a mission life of < 90 days (e.g., Ag-Zn). Furthermore, the MER Li-ion battery, aided by a JPL-developed low temperature electrolyte, could operate well at sub-zero temperatures, down to -30°C, as well as ambient temperatures (40°C), which reduces the thermal management, its mass and size. These batteries were located in the aerogel-insulated Warm Electronics Box. Using a combination of resistive heaters, radioisotope heating units (RHUs) and thermal switch activated-Loop Heat Pipe heat rejection system, the rover batteries are being controlled thermally between -20°C to +30°C.

The role of the lithium-ion batteries is three-fold. They were designed to provide about 200 Wh during launch, about 160 Wh during cruise for supporting Trajectory Control Maneuvers (TCM), and about 280 Wh for surface operations. In addition, the rover batteries were designed to provide energy to fire three simultaneous pyros, as a backup to the primary Li-SO₂ batteries on the lander (each with a load of 7 A), either during the Entry-Descent and Landing (EDL) sequence, or in the processes leading to the rover egress from the lander. Finally, there was a need for redundancy, i.e., the minimum energy needs of the mission to be met even with the loss of one battery. To meet the above requirements, both the Spirit and Opportunity rovers have two parallel lithium-ion batteries, each with eight 10 Ah cells in series. The batteries were fabricated by Yardney Technical products, or currently Lithion, located in Pawcatuck, CT, using the same chemistry that was developed earlier for MSP01 Lander missions.⁵ This chemistry utilized our first generation low temperature Li-ion battery electrolyte, i.e., 1 M LiPF₆ dissolved in equi-proportion ternary mixture of ethylene carbonate, dimethyl carbonate and diethyl carbonate.⁶ In addition to a good low temperature performance, this chemistry showed excellent calendar and cycle life, much more than desired by the rover missions, and also a wide operating temperature range of -30 to +40°C.⁷

In this paper, we briefly describe the design of the lithium-ion batteries on the Mars Exploration Rovers. Furthermore, the performance characteristics of these batteries on both Spirit and Opportunity during launch, cruise and surface operations on Mars are described here.

MER Rover Li-ion Batteries

The rover battery assembly unit was comprised of two parallel Li-ion batteries, each containing eight prismatic, 10-Ah, Li-ion cells. These cells were specifically designed for the MER program, based on the envelope available for the battery in the Warm Electronics Box of the rover. The battery housings were designed and fabricated at JPL. A notable feature of the battery housing was to ensure that the preload on each battery was maintained, even with the loss of the other battery, to ensure redundancy. This was partly ensured by a divider plate between the two batteries, that would provide the required pre-load on the battery, even in the event a cell venting from the other battery. Likewise, each battery is electronically-independent of the other, with individual Battery Control Boards (BCBs) to control the battery charges and discharges within specified voltage limits. These BCBs were designed and fabricated at JPL to monitor and control individual cell voltages in both the batteries and thus to prevent overcharge or overdischarge of any cell. The cell balancing during charge was accomplished via individual cell bypass through a 120 ohms resistor. Four different charge voltages, i.e., 3.85, 3.95, 4.15, and 4.20V may be programmed (thus termed as command voltage, V_{com}) from ground to allow the battery to be charged to ~ 50%, 80%, 100% and a little over 100% (in the latter parts of the mission, if needed) respectively. Charging of the cells is permitted only the cell voltages are at least 150 mV lower than the command voltage and will be stopped when the voltage of any cell exceeds the command voltage or when all the cells get into the bypass mode. The cell bypass starts when the cell voltage approaches within 30 mV of V_{com} , and ends when the cell voltage drops below 70 mV of the V_{com} . Likewise, the discharge of a cell is permitted only its voltage is higher than 3.4 V and ended if it drops below 2.9 V. This scheme of charge/discharge control of the lithium-ion batteries worked successfully to avoid their overcharge and overdischarge, while providing good cell balance, as evident in the performance data provided below.



Fig.1: Li-Ion Rechargeable Battery Assembly Unit on the Mars Exploration Rovers, Spirit and Opportunity.

Several battery parameters were followed via telemetry during the mission. These include individual battery voltages (two per rover), individual cell voltages (eight per battery and sixteen per rover), rover battery current (one per battery and two per rover) and four battery temperatures (four per rover). The four temperature probes (PRTs) are located on two end cells, one on the middle cell and on the battery casing.

Initial performance of Spirit and Opportunity Li-Ion Batteries

As part of the receiving inspection and acceptance testing, the flight batteries were subjected to capacity measurements at ambient as well as low (-20°C) temperatures and 72-hour charge stand test. These tests were performed about three months after the battery fabrication or about six months after the cell activation. The initial discharge characteristics of the two batteries on MER-A or Spirit are illustrated in Fig.2.

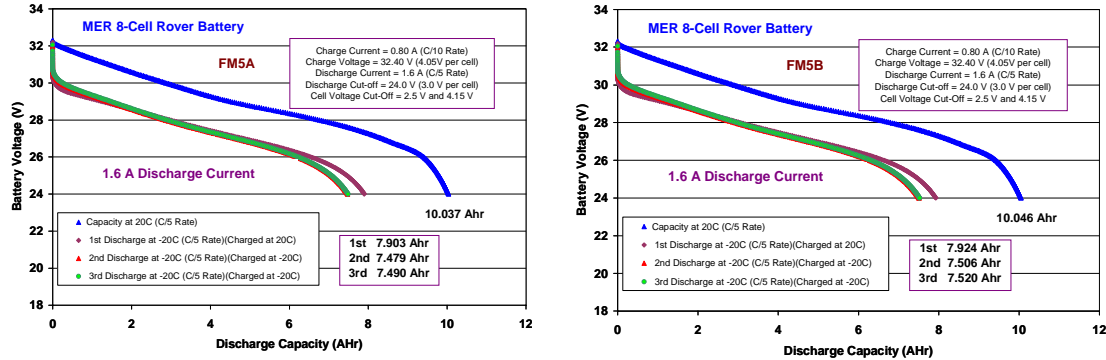


Fig. 2: Initial discharge characteristics of the Li-ion battery assembly unit on Spirit rover.

The batteries A and B showed an initial capacity of 10.037 and 10.046 Ah at 20°C . The corresponding capacities at -20°C and C/5 are 7.49 and 7.52 Ah, respectively. The maximum cell divergence in the Battery A, at -20°C , is 14 mV at the end of charge, while at the end of discharge the divergence increased to 31 mV. The corresponding values for the Battery B are 19 and 95 mV, respectively.

Similar tests performed on the batteries A and B of the Opportunity rover showed capacities of 10.042 and 10.047 Ah at 25°C , respectively. Their corresponding capacities at -20°C are 7.464 and 7.562 Ah, respectively (Fig. 3). The voltage differential between strongest and the weakest cell is 41 mV during charge and 141 mV during discharge at -20°C in the case of Battery A. Battery B showed divergence of 28 mV and 85 mV during charge and discharge at -20°C , respectively.

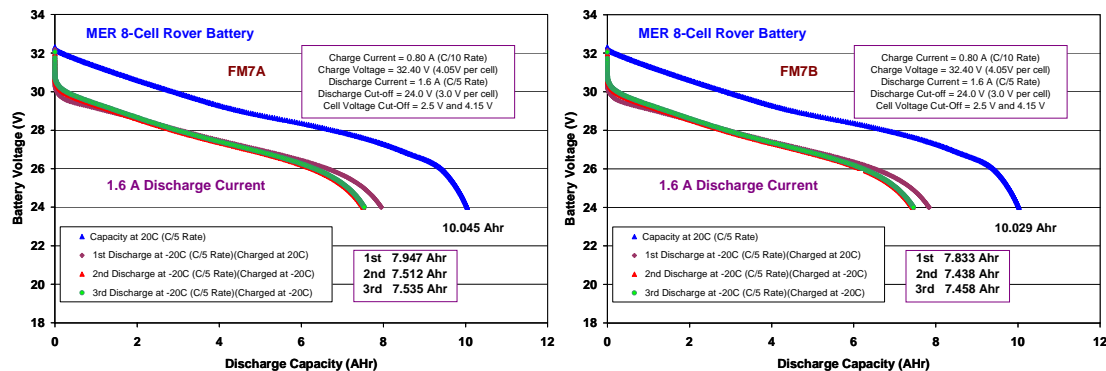


Fig. 3: Initial discharge characteristics of the RBAU on the Opportunity rover.

As may be seen from Figs. 2 and 3, both the batteries in each of the RBAUs showed good performance characteristics, combined with low cell divergence, even at low temperatures. This was made possible largely due to the care exercised in cell fabrication and especially in cell matching. Various performance characteristics with appropriate weightings were taken into account, while handpicking cells for the batteries. Such quality cell fabrication combined with judicious cell matching would go along way in terms of battery's durability and mission longevity, as also demonstrated by the in-flight data here.

In-Flight Performance of Li-ion Batteries

Launch and Cruise

As mentioned before, the Li-ion batteries on the MER were designed to provide about 200 Wh during launch at ambient temperatures, which corresponds to about 50% depth of discharge, if both batteries were functional and fully charged to 32.8 V. Subsequently, the battery state of charge was to be adjusted to ~ 80% to support cruise anomalies, which include trajectory control maneuvers. In addition to being at low state of charge, the batteries were held at a low temperature as well during cruise, with the temperature of decreasing from an initial value of 15°C to a final value of -10°C during cruise. These measure were recommended with the objective of minimizing the permanent loss in the battery capacity during on-buss storage in cruise.⁸ The cruise anomaly corrections required about 160 Wh, which would be a challenge for single battery to support, especially at -10°C. However, as illustrated below, the rovers didn't experience any such cruise analogy, such that the rover batteries were not subjected to any discharge during cruise. Fig. 4 shows the behavior of the first Li-ion batteries on the Spirit during launch and cruise. The batteries on the Opportunity rover showed similar behavior.

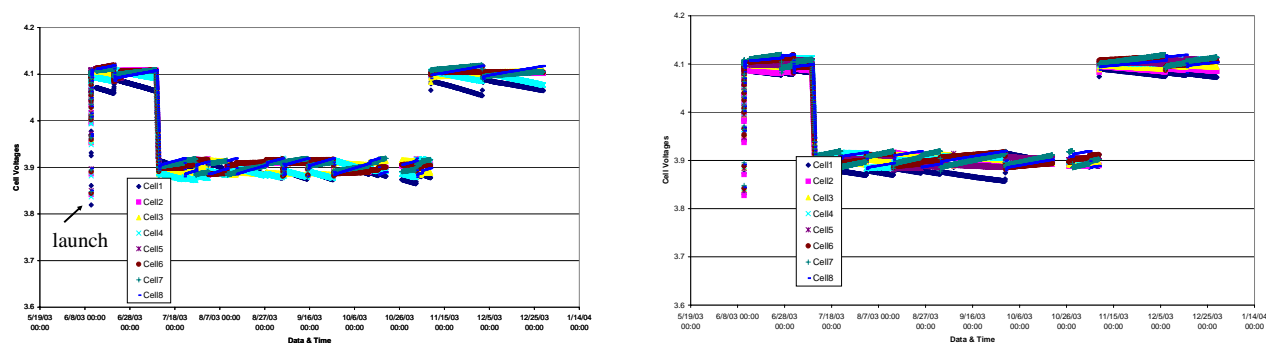


Fig. 4: Behavior of Li-ion batteries on the Spirit during launch and cruise

As may be seen from the figure, each battery was discharged to about 25% depth of discharge per battery during launch, with lowest cell voltages being 3.82 V. After launch, both the batteries were fully charged and were maintained at the state of charge for about a month, due to the mission personnel being tied up with the launching of the second rover, Opportunity. In this one-month duration, the individual cell voltages showed slight divergence a couple of time, to probably beyond 140 mV, which prompted the implementation of cell balance through by-pass. Subsequently the state of charge in both the battery assembly units was brought down to 80% and maintained over a period of four months, from mid-July through mid-November. Once again, during these four months, the cell divergence increased beyond 140 mV, followed bypass and cell rebalance, for about 6-8 times. Later, about a month before landing on Mars, the batteries were charged back to 100% state of charge, to be ready for the Entry Descent and Landing (EDL) Operations, if required, and for immediate surface operations. The behavior of the Li-ion batteries on the second rover, Opportunity is similar to these batteries.

Performance on Mars Surface

The rovers, spirit and Opportunity have successfully completed the primary mission of 90 Martian sols and are currently in the extended phase of the missions. Specifically, Spirit has thus far completed about 550 sols and Opportunity has about 525 sols to its credit. The lithium-ion batteries have been performing quite well and providing impressive support to the mission. Fig. 5A and 5B sum up the performance of the battery assembly units on Spirit and Opportunity.

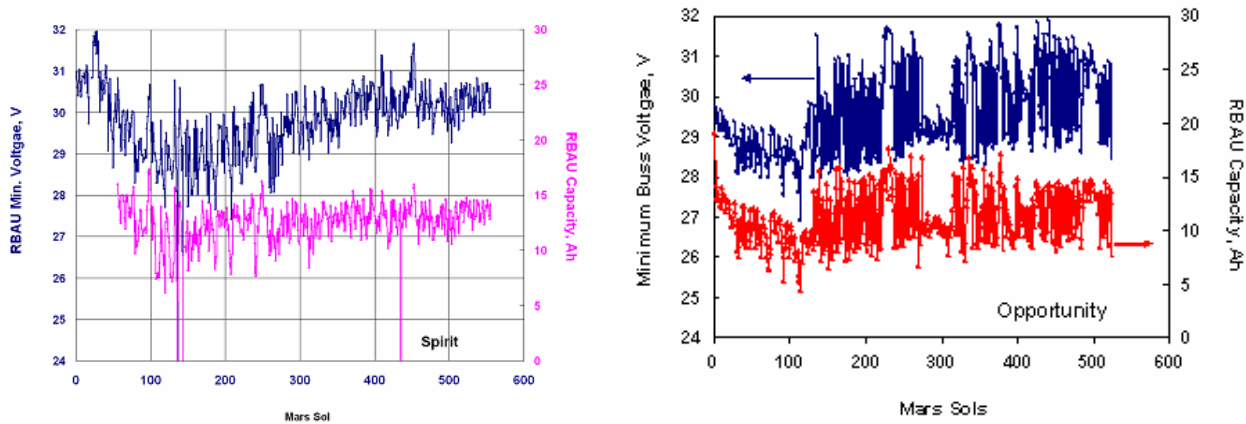


Fig. 5: Summary of RBAU performance on Spirit and Opportunity

There was a software-related anomaly around sol 20 for the Spirit, when the batteries were completely discharged and were recharged only after a few days. This anomaly, however, didn't affect their subsequent performance. The minimum RBAU voltages or the battery end of discharge voltages are above 28 V. The maximum discharge (or charge) capacity is little more than 10 Ah voltage, i.e., 50% depth of discharge for the RBAU (Fig. 5). Based on the high RBAU voltage, it may be inferred that both the batteries in these RBAUs have been functioning well, sharing the load (and energy) between them. This low DOD in turn will have considerable benefit on the cycle life that may be expected from these batteries, especially when the operating temperatures are low.

Apart from the batteries in the RBAUs matching well in terms of their load share, the cells within a battery showed good balance in terms of their voltages. Fig. 6 shows the typical individual cell voltages in the first battery of Spirit and Opportunity, respectively.

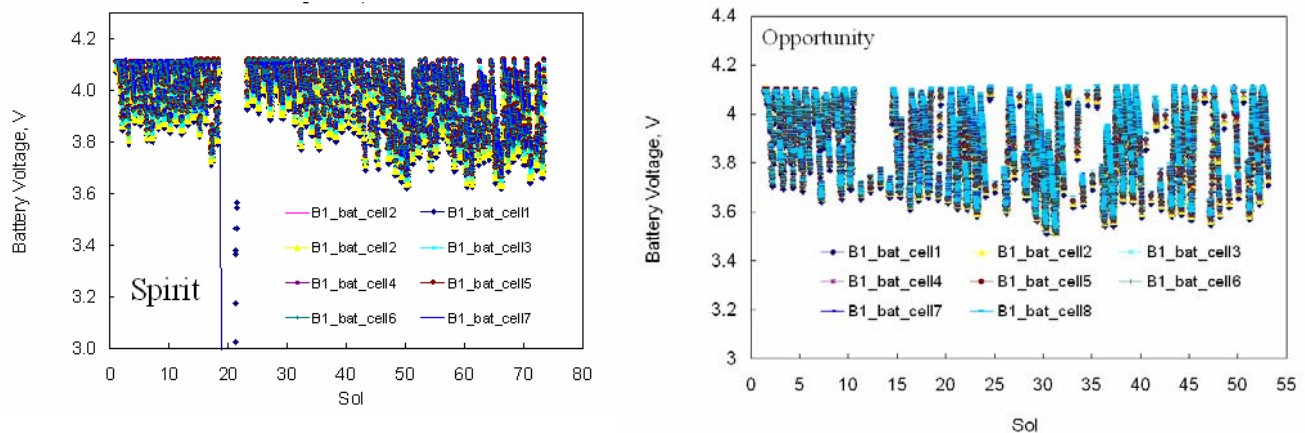


Fig. 6: individual cell voltages in one of the two batteries on the Spirit and Opportunity.

The cell divergence was low at the beginning of the surface exploration, due to the cells being balanced before the EDL. Subsequently the cell divergence continued to increase with each sol. However, this didn't pose any problem, since the cells would be balanced if the divergence exceeds 150 mV. Figure 7 shows the cell divergence in both the batteries of the Spirit. This maximum cell divergence here includes the divergence during charge as well as discharge.

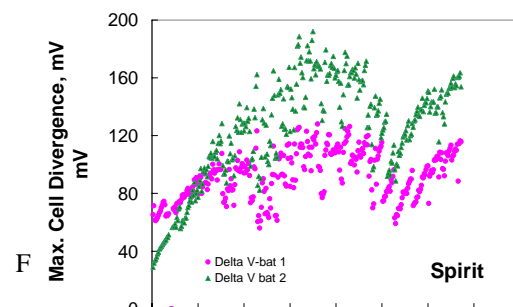


Fig. 7 Maximum cell divergence in the batteries of the Spirit

Due to the thermal control provided in the form of radioisotope heater unit (RHU) and additional survival foil heaters units around the batteries, and thermal switch activated-Loop Heat Pipe heat rejection system, the battery temperature has been maintained between -20 to 30°C . Fig. 8 shows the maximum and minimum daily temperatures over 500 Mars sols for the Spirit and Opportunity rovers. The batteries on the Spirit have experienced a continuous decrease in the minimum temperatures to $\sim -18^{\circ}\text{C}$ till sol 200 followed by an increase back to the initial values of 10°C . This is consistent with the seasonal pattern on Mars. The Opportunity rover, on the other hand, has higher temperatures of 5 - 10°C and the trend is not as smooth as with the Spirit. This may be related to problem of one of its heaters losing control and being locked in the 'on' position.

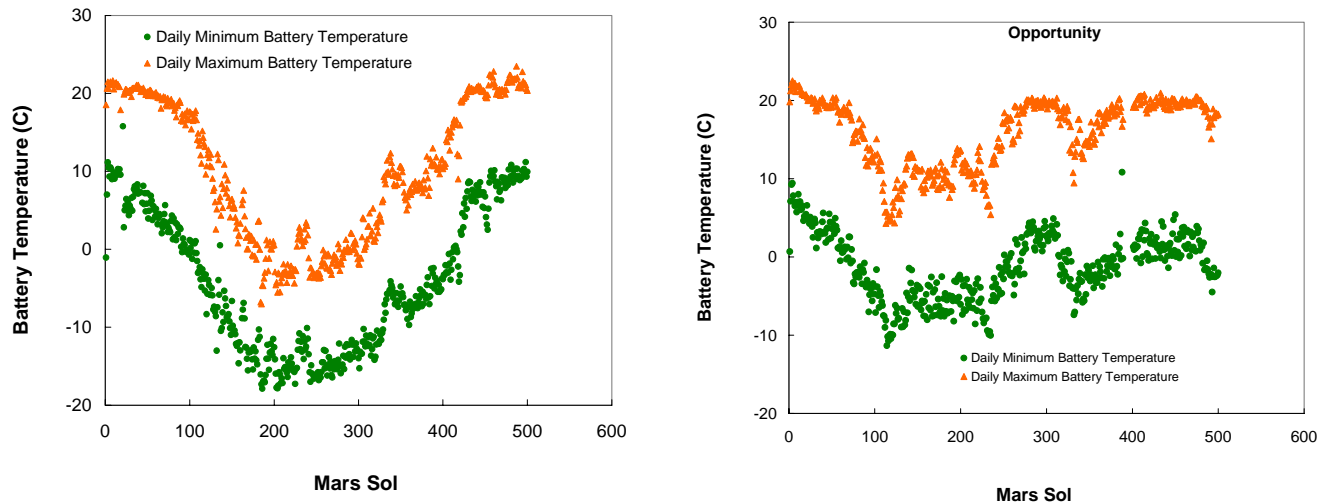


Fig. 8: Temperature of the RBAs on Spirit and Opportunity

Projection on Mission Life

After over 550 cycles into the Mars expiration, the energy conversion system as well as energy storage device, i.e., solar arrays as well as the Li-ion batteries have performed well beyond the expectations. The solar array for example lost power in between due to dust accumulation on the panel, which subsequently cleared by itself. As a result, the solar array recovered almost totally, currently displaying daily energy values of ~ 700 Wh, with peak currents of over 3 A (Fig. 8). The Li-ion rechargeable batteries, on the other hand, have healthy discharge (minimum) voltages, indicating little degradation in their capacity. The ground tests being performed on the mission simulation battery (see our companion paper⁹) estimate the capacity loss in the MER batteries is 5-10% thus far. Both the solar arrays as well as the batteries are therefore expected to continue providing power to the Sprit and Opportunity rovers through over 1000 sols and thus extend the Martian surface to \sim three years.

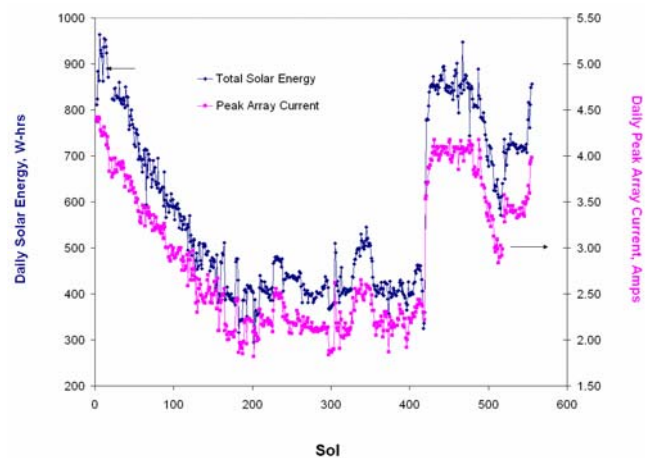


Fig. 8. Solar array performance on the Spirit

Conclusions

Li-ion batteries provided the heart beat for the Mars Exploration Rovers. Prompted by the constraints on mass and volume, as well by their high specific energies combined with good low temperature batteries, these batteries enhanced the capabilities of these missions significantly, compared to the conventional aqueous

rechargeable batteries. After about 550 cycles and 550 days of surface exploration and about three years after their fabrication, these batteries have very healthy discharge characteristics. Based on the ground tests on the mission simulation batteries, it is clear that there is very little performance degradation in the rover batteries, and these batteries are certain extend the rover missions from a few months to a couple of years. Finally, there will be several future missions that can be equally befitted by these Li-ion batteries, including the upcoming Mars surface missions, i.e., Phoenix Lander in 2007 and Mars Science Laboratory (MSL) in 2009.

Acknowledgements

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